

Joint Robotics Program (JRP)-supported efforts at the Space and Naval Warfare Systems Center, San Diego

Hoa G. Nguyen* and H.R. Everett

Space and Naval Warfare Systems Center, San Diego, CA 92152-7383

ABSTRACT

The Space and Naval Warfare Systems Center, San Diego (SSC San Diego) is conducting a number of robotics research, development, evaluation, fielding, and combat-support missions and projects in support of Joint Robotics Program (JRP) goals. These include: Man-Portable Robotic System, Unmanned Surface Vessel, Automatically Deployed Communication Relays, Autonomous UAV Mission System, Robotic Systems Pool, Family of Integrated Rapid Response Equipment, and the Technology Transfer project. This paper summarizes the recent accomplishments and current status of these efforts, many of which are individually presented in more detail elsewhere at this conference.

Keywords: JRP, robotics, SPAWAR, UGV, USV, UAV

1. INTRODUCTION

The Space and Naval Warfare Systems Center, San Diego (SSC San Diego), and its predecessor organizations have been pioneers in the field of mobile robotics for over 40 years. This legacy started with unmanned underwater vehicles (UUVs) at the Naval Ordnance Test Station, one of SSC San Diego's parent laboratories, in the early 1960's¹ and continued with the formation of the ground robotics group at the Naval Ocean Systems Center in the early 1980's.^{2,3} Several reorganizations and name changes later, SSC San Diego now has a large and dynamic group of engineers and scientists performing unmanned systems research and development in all operational domains (i.e., land, sea, and air), as well as supporting the U.S. Department of Defense fielding of robots in various theaters. The SSC San Diego Unmanned Systems Branch currently has close to twenty parallel robotics projects, seven of which are supported by the Office of Secretary of Defense (OSD) Joint Robotics Program (JRP). This paper briefly reviews these seven projects (sections 2 through 8), and describes a recent collaborative demonstration that showcased their autonomous capabilities.

2. MAN-PORTABLE ROBOTIC SYSTEMS (MPRS)

The purpose of the Man-Portable Robotic System (MPRS) project is to increase the autonomous capabilities of small robots by developing and transferring technologies that will have an immediate impact on the autonomy and capability of current man-portable robotic systems. Tele-operated systems have proven to be very useful, but only in life-threatening situations or where extremely precise manipulation is required (e.g., explosive ordnance disposal applications). MPRS is focused on adapting technologies that have been developed for larger unmanned ground vehicle systems to the man-portable class of robots, as well as developing miniature sensors suitable for use on this class of robots. These technologies will increase the autonomy in small robots and lessen the burden on the operator of manually driving the vehicle. Specific technologies include navigation, obstacle detection/obstacle avoidance (ODOA) and collaborative behaviors for small vehicles. The technology demonstration platform for MPRS is the SSC San Diego Urban Robot (URBOT, see Figure 1), previously developed under this same project.

Recent accomplishments for MPRS include:⁴

1. Development of enhanced non-differential-GPS waypoint navigation for man-portable robots.⁵
2. Development, in conjunction with the Jet Propulsion Laboratory (JPL), of a miniature stereovision-based obstacle-detection and collision-avoidance sensor (the JPL *SmartCam*) suitable for small mobile robots.

* Email: hoa.nguyen@navy.mil

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3. Design and development of a behavior based, reactive obstacle-avoidance algorithm matched to the capabilities and constraints of the miniature stereovision system.
4. Development of a prototyped chemical/radiation/gas sensor suite for small robotic systems. This technology was subsequently transitioned to SSC San Diego's Tactical Mobile Robots and Robotic Systems Pool projects (see Section 8), as well as to iRobot Corporation and Mesa Robotics, Inc.
5. Initial demonstration of small robot formations using the Geodetics *Epoch-by-Epoch* relative GPS system.
6. Conversion of MPRS software to the Joint Architecture for Unmanned Systems (JAUS) standard.

MPRS is currently performing spiral development on the stereovision technology, continuing to work with JPL to develop a second-generation miniature processing board and navigational software.



Figure 1. The MPRS URBOT and its backpack controller.

3. UNMANNED SURFACE VEHICLE (USV)

The goal of the SSC San Diego USV project is to develop technologies—in particular, autonomous surface navigation technologies—for transition to other unmanned assets and programs. A *Seadoo Challenger 2000* sport boat with jet drive was chosen as the technology development platform due to its low cost, ease of systems integration, low maintenance, payload capacity, and performance similarity to operational USVs.

Our approach for the development of USV autonomy is to pursue robust transition-ready capabilities, and progressively build upon initial success with more sophisticated and enabling functionality. Much of the technology has been adapted from our earlier UGV programs, due to the similar two-dimensional nature of surface and ground navigation, to include: 1) teleoperated control, 2) navigational sensor fusion using Kalman filtering, 3) waypoint navigation, and 4) multi-vehicle command and control.⁶ These command and control (C2) technologies have been adopted for use on the Naval Undersea Warfare Center's Spartan Scout ACTD and the Navy's Littoral Combat Ship USV program. In 2004, at the request of SSC San Diego's Intelligence, Surveillance, and Reconnaissance Department, we demonstrated autonomous deployment of fiber-optic cable on the ocean floor at 35 knots using GPS waypoint navigation (see Figure 2).

At present, SSC San Diego is primarily focused on obstacle-avoidance (OA) technologies for the USV.⁷ We adopted a two-tiered approach consisting of a near-field reactive OA component and a far-field (>200-300 m) deliberative OA component, which simultaneously operate in conjunction with one another. The primary function of the deliberative component is to continuously modify the waypoint route to plan around obstacles detected by the long-range sensors. The reactive OA component, meanwhile, is responsible for avoiding obstacles in close proximity, regardless of the vehicle's mode of operation or mission.



Figure 2. The USV demonstrating autonomous deployment of fiber-optic cable.

The deliberative OA component obtains data from Digital Nautical Charts (DNC) and a Furuno marine radar, and uses the standard A* algorithm to plan paths around static obstacles. Handling moving obstacles is a much harder problem. To keep the time required to generate a valid path manageable, the path planner translates the time dimension of a moving obstacle into a two-dimensional projected area. Taking nautical rules of the road into account, it then issues navigational commands to circumnavigate these projected areas, keeping the USV as close as possible to the original path.

Based on data from near-field sensors (i.e., stabilized vision and ladar), as well as DNC and radar, the reactive OA component modifies the teleoperation or driving commands from the navigator before execution by the control actuators. All messages between USV subsystems conform to the JAUS standard.

4. TECHNOLOGY TRANSFER (TECHTXFR)

The JRP Technology Transfer (TechTXFR) project employs a spiral-development process to enhance the functionality and autonomy of mobile robot systems, including those currently being used in theater to address the threat of improvised explosive devices (IEDs). This is accomplished by assessing the maturity level of robotic technologies developed in the research environment and advancing their Technology Readiness Levels (TRLs) for testing and demonstration in an operational environment. The project harvests prior and on-going developments from a variety of sources to address technology needs identified by emergent in-theater requirements and the users of the JRP Robotic Systems Pool. The component technologies are tested and evaluated on transition platforms to identify the best features of the different approaches, which are then integrated and optimized to work together in a complete solution. TechTXFR has teamed with a number of organizations with similar ambitions, both government and academia, to synergistically pursue robotic technologies in a spiral development process.

Significant accomplishments to date include:

1. Integrated and evaluated SRI International's ladar-based simultaneous-localization-and-mapping (SLAM) algorithm with the Idaho National Laboratory's (INL) collision-avoidance algorithm. Further enhanced SLAM to use particle filters to maximize computational efficiency. Developed a gradient-based path-planning algorithm for use on the SLAM occupancy grid to generate motion trajectories to a specified goal position while avoiding obstacles in the environment. This combination allows an autonomous robot to map its immediate surroundings, determine its current location, and relocate to any destination selected on the map. This technology was ported to an iRobot *ATRV*, which was able to autonomously map an entire underground WW-II bunker with no a priori knowledge. The resulting map was then uploaded to a remote operator using low-bandwidth (9.6 Kbaud) wireless serial communications.

2. Enhanced vision-based object-recognition and tracking algorithms based on the Distributed Interactive Video Array (DIVA) technology originally developed at University of California, San Diego. This capability provided automated target recognition, assessment, and response for non-lethal weapon control on a robotic platform.
3. Integrated technologies from Brigham Young University, INL, and SRI to create an “augmented virtuality” interface (see Figure 3). The SLAM-generated world model used for indoor world representation, while onboard sensor payloads augment the virtual environment with additional data (i.e., real-time images, sensor readings) to create a robust situation-awareness solution compatible with low-bandwidth links.
4. Further extended SRI’s SLAM algorithm to support lidar-based intruder-detection-on-the-move.
5. Integrated the University of Southern California’s *Player/Stage Device Server* (a robotic development environment now used by numerous institutions) with INL’s *Advanced Robotic Control Architecture (ARCA)* to provide a standardized interface allowing multiple control algorithms to access robot devices (i.e., sensors, actuators). This approach enables a reconfigurable software framework that can be easily ported from one robotic system to another.
6. Integrated JAUS messaging with *ARCA*.

To showcase the above accomplishments to the user and technical communities, the TechTXFR project recently demonstrated seamless indoor/outdoor navigation, integrating GPS technology with SLAM, Markov localization, and Kalman filtering.⁸ This is the first step in enabling autonomous robotics to cross from the research domain into possible real-world applications.

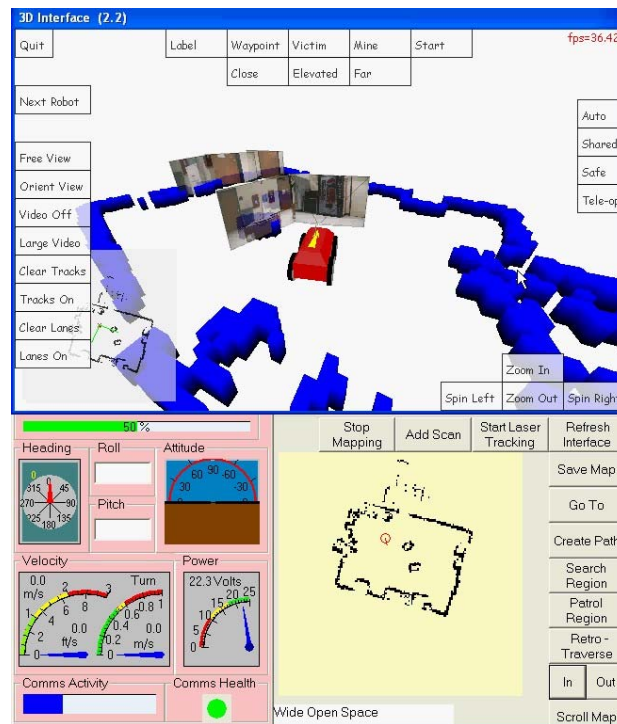


Figure 3. Augmented-virtuality interface, showing map generated by SLAM algorithm merged with live video data.

Future technology focus areas include: 1) fusion of optimized detection and recognition techniques (i.e., vision, lidar, microwave correlation, radiometer) with the SLAM map to further enhance the augmented-virtuality display with identified objects of interest, and 2) the cooperative control of heterogeneous robots (i.e., an autonomous UGV teleoperating a micro-UAV, UGV, etc.).

5. AUTOMATICALLY DEPLOYED COMMUNICATION RELAYS (ADCR)

The ADCR project is addressing a critical user-requested capability upgrade: to automatically maintain a robust radio frequency (RF) communication link between a tactical robot and its associate controller. We are developing a “Relay Deployment Module” that can be attached to the robot, which automatically monitors link quality and drops a “Relay Brick” when and where needed to ensure effective comms throughput.

ADCR heavily leverages earlier work on the Autonomous Mobile Communication Relays (AMCR) project, a previous DARPA-funded effort at SSC San Diego.^{9,10} Under AMCR, RF relays were carried on small slave robots that autonomously followed the lead robot. These slave robots stopped where needed to provide an ad hoc network that maintained link integrity. The intelligence and mobility of these relay nodes allowed more sophisticated behaviors, such as repositioning or recovery at the end of the mission. While shown to be effective, this earlier approach was not practical for field use, where system cost and logistics support must be taken into account.

ADCR makes use of the ad hoc networking hardware and software from AMCR, as well as the intelligent-deployment decision-making algorithm—the command for the mobile relay robot to stop (under AMCR) occurs at exactly the same point where a Relay Brick would be dropped (under ADCR). While the algorithm is distributed under AMCR (i.e., each relay robot decides when to stop by monitoring the link to the node behind it), under ADCR the Deployment Module monitors the network and issues commands to drop the relay bricks.

Additional issues addressed under ADCR include building a self-righting, rechargeable, and waterproof Relay Brick containing the radio repeater, and development of the Deployment Module and associated electronics. Each ADCR system carries six Relay Bricks (see Fig. 4), which self-right when dropped and automatically extend an antenna 60 cm into the air (see Figure 5). The chosen height reflects a tradeoff between small size (i.e., compatible with a man-portable robot) and desired range (approximately 500 meters between nodes over sandy soil), as determined through computer simulation.

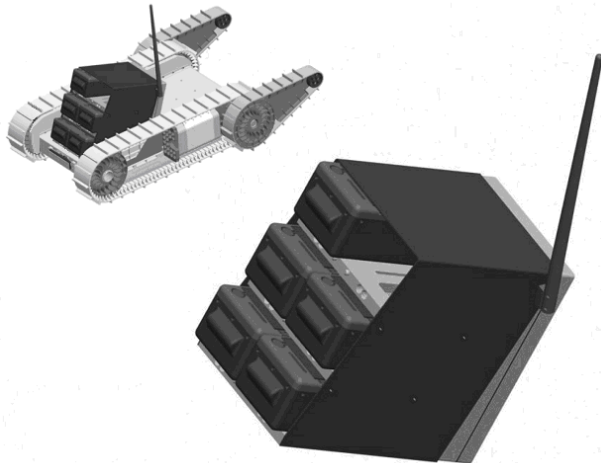


Figure 4. Model of Deployment Module, stand alone (right), and installed in the payload bay of an iRobot *PackBot* (left).



Figure 5. The prototype Relay Brick automatically self-rights and deploys its antenna.

The Deployment Module can be interfaced with any IP-based communication system through an Ethernet port. At the operator end, another Relay Brick provides an identical interface to the operator control unit (OCU) through its Ethernet port. Robots equipped with analog communication links can be converted to IP-based compatibility with commercially available coder/decoder (CODEC) boards.

Four identical ADCR prototype systems are being produced, one at the request of the Naval EOD Technology Division (NAVEODTECHDIV) for use on the MTRS *PackBot*, two for use on the *TAGS-DM* and *Wolverine* robots at the Army

Tank Automotive Research Development and Engineering Center (TARDEC), and the fourth for in-house testing and spiral development on the SSC San Diego Urban Robot (URBOT).

6. AUTONOMOUS UAV MISSION SYSTEMS (AUMS)

AUMS addresses one of the biggest disadvantages of vertical-take-off-and-landing (VTOL) UAVs: their limited flight endurance. AUMS provides forward staging, launching, recovery, refueling, and re-launching capabilities for the VTOL UAV from a host UGV or stand-alone structure.¹¹ The host UGV provides a means of forward deploying a small UAV into hazardous areas unsafe for personnel, such as chemically or biologically contaminated areas. AUMS is also the SSC San Diego part of the joint-services JRP-sponsored Collaborative Engagement Experiment project,¹² which provides the framework for developing and demonstrating collaborative behaviors between UGVs and UAVs.

Initial AUMS design and development focused on use with the AAI *iSTAR* 29-inch lift-augmented-ducted-fan UAV platform. Subsequently, a variety of teleoperated and autonomous helicopters, such as the Rotomotion *SR100*, have been adapted as low-cost technology-development surrogates for the *iSTAR* UAV. The helicopters are modified for use with AUMS by incorporating ring-shaped landing gear similar to that of the *iSTAR* platform. An early prototype of the Army's Mobile Detection Assessment Response System (MDARS) physical security robot has been used as the host UGV (see Figure 6).



Figure 6. The AUMS configuration with the MDARS UGV and iSTAR UAV.
The refueling system can be seen attached to the back of the UGV.

The AUMS development schedule is divided into four major phases: Launch, Recovery, Refueling, and Command and Control. Four prototypes of the launch/recovery platform have been designed, each incorporating lessons learned from previous versions. The final configuration includes:

1. A vented landing surface that minimizes “ground effect” for greater stability during recovery.
2. Active centering arms that move the UAV towards the center of the platform upon touchdown.
3. A passive self-centering adapter that is used both as a refueling coupler and a latch. The adapter is free to move laterally to accommodate slight misalignment between the platform and the UAV. It also secures the

UAV during launch, releasing only when the engine has reached full thrust to help the UAV quickly clear the area containing antennas and sensors on the UGV.

Various sensor technologies have been examined by SSC San Diego for use in the precision landing phase. These technologies include a Novatel RTK differential GPS, a highly accurate relative-positioning GPS technology using low-cost receivers from Geodetics, a vision-based positioning system from Carnegie Mellon University that relies on near-infrared beacons arranged in a structured pattern on the UGV, a small lightweight vision-based target tracking and landing algorithm from the University of Southern California, and the government-developed Joint Precision Landing System. (This last option is currently too large and requires a differential GPS correction signal that may not always be available in tactical operating environments.)

Currently we are evaluating a low-cost near-infrared beacon system called *NorthStar* produced by Evolution Robotics, which was originally designed for localization within an enclosed space using a fixed optical projector and an associated detector on the moving object. The final solution will incorporate GPS for coarse localization and an optical solution for precision alignment during final approach.

AUMS is designed to operate without knowing the current fuel level of the incoming UAV, as most small UAVs do not have fuel-gauge sensors. By incorporating a bidirectional pump, AUMS completely de-fuels and then refuels the UAV to the desired level. The system also incorporates automatic shut down upon leak detection, as well as a passive fire-suppression system.

AUMS uses the Multi-robot Operator Control Unit (MOCU) software developed by SSC San Diego for command and control.¹³ MOCU is a JAUS compliant system designed specifically for simultaneously controlling multiple heterogeneous unmanned systems, including UGVs, USVs, and most recently, VTOL UAVs. In an AUMS scenario, MOCU allows a single operator complete control over UxV mission planning, positioning, sensor data, payload control, and system status.

7. FAMILY OF INTEGRATED RAPID RESPONSE EQUIPMENT (FIRRE)

The Family of Integrated Rapid Response Equipment (FIRRE) is an advanced technology demonstration program to develop a family of affordable, scalable, modular, and logistically supportable unmanned systems to meet urgent operational force-protection needs worldwide. The near-term goal is to provide the best available unmanned ground systems for protection of warfighters in the Iraq and Afghanistan theaters. The overarching long-term goal is to develop a fully integrated layered force-protection system of systems for forward-deployed forces, which can be networked with the future-force C4ISR systems architecture. The intent of the FIRRE program is to reduce manpower requirements, enhance force-protection capabilities, and reduce casualties through the use of unmanned systems.^{14,15,16}

FIRRE has been designed for rapid deployment in support of emergent tactical missions, or permanently integrated into base operations as part of a complete force-protection package. As a system of systems, its configuration is flexible and scalable, with the exact mix of equipment for a particular application based upon mission, enemy, troops, terrain, and time. A nominal deployment would consist of a single C2 station controlling multiple unmanned assets operating over an area of approximately 100 square kilometers. The C2 Station is a self-sustaining mobile command post housed in an *S-788 TYPE I* shelter that rides on an *M1152* HMMWV.¹⁴ A typical FIRRE system (Figure 7) for performing perimeter security of a moderate-sized (i.e., 7 x 5 kilometers) ammunition base could include:

- 1 M1152 HMMWV
- 1 S-788 TYPE I Shelter housing C2 Station Equipment
- 6 Blue Sky Masts with Radio Antennas
- 1 PU798 10KW Generator Trailer
- 2 M1102 Support Equipment Trailers
- 4 Remote Sensor Stations (RSS)
- 50 BAIS Unattended Ground Sensors
- 2 FIRRE Unmanned Ground Vehicles (UGV)



Figure 7. FIRRE C2 Station (left), RSS (middle), and UGV (right)

Each RSS is comprised of four major subsystems: sensors, tower, electronics, and power.¹⁵ Deployment of the RSS requires 4-6 persons and between 2-4 hours, depending on training, weather, and soil conditions. In its current configuration, the RSS supports a ground-surveillance radar (GSR), unattended ground sensors (UGS), and a thermal/visual imaging system (TIS/VIS) sensor package. The RSS is deployed at the perimeter of the area of interest to provide remote sensing to the extents of the equipment's capabilities. Video feeds and sensor data are processed by the embedded computer in the RSS electronics box and sent back to the C2 station for display within the Joint Battlespace Command and Control System for Manned and Unmanned Assets (JBC2S).¹⁶

The FIRRE UGV, developed by Northrup-Grumman/Remotec, is a tracked vehicle capable of off-road operation. The UGV has a differential-GPS waypoint navigation system, and an obstacle-detection system consisting of a front-mounted SICK ladar and six MA-Com radars installed around the vehicle perimeter. The UGV is also equipped with an *AN/PPS-5D* ground surveillance radar for detecting personnel and vehicles, with a speaker and microphone to allow the operator to interrogate an intruder.

Over a 9-month period, the FIRRE Integrated Product Team developed an “80-percent solution” that is affordable, supportable, uses military equipment where possible, or readily available commercial equipment where practical. The resulting system has been demonstrated in two week-long field exercises at Hawthorne Army Depot in Nevada over an operational area in excess of 35 square kilometers. Current plans call for participation in a July-August 2006 Comprehensive Force Protection (CFPI) Demonstration at Yuma Proving Ground, Arizona. FIRRE will eventually integrate with the Counter-Rocket, Artillery and Mortar (C-RAM) program as part of the U.S. Army Maneuver Support Center’s 360-degree Comprehensive Fixed Site Protection concept. If successful, this integrated effort will be deployed in FY-07 to provide a force-protection capability against indirect fire and ground intruders.

8. ROBOTIC SYSTEMS POOL (RSP)

The Robotic Systems Pool (RSP) is a consolidated collection of man-portable robots to be loaned to government agencies, laboratories, and universities, intended to assist in defining requirements as well as developing tactics, techniques, and procedures. The robots are commercial-off-the-shelf (COTS) systems available from several manufacturers (see Figure 8). RSP personnel collect evaluation reports from experiments conducted with the robots and provide feedback to the manufacturers for future technology upgrades. This process helps to accelerate improvements in robotic systems over the traditional acquisition cycles. RSP loan priority goes to DoD organizations, homeland security and emergency response users, and research and academia, in that order. Figure 8 shows examples of pool assets.

When appropriate, RSP assets are supplemented with unique payload and/or platform modifications to address emerging operational and programmatic requirements, often accomplished with supplemental funding from requesting organizations. In 2003, for example, SSC San Diego developed a chemical/radiological sensor (CHARS) package for the US Army Chemical School at Fort Leonard Wood, Missouri, designed to ultimately be a plug-and-play payload on a



Figure 8. Examples of RSP assets.

variety of man-portable robots (i.e., *URBOT*, *Talon*, and *Matilda*). We subsequently issued a contract to iRobot to reproduce these systems for the *PackBot*, based on the SSC prototype. Four *PackBots* equipped with CHARS payloads were delivered to the Army XVIII Airborne Corps for deployment to Iraq in November 2003, supported by the Robotic Systems Joint Program Office.¹⁷

Later, as the perceived threat shifted from weapons of mass destruction to IEDs, the CHARS units were swapped out for manipulator payloads that could be used to neutralize the IEDs. User feedback soon indicated a problem with premature manipulator failures resulting from attempts to excavate buried IEDs, a task for which they were not originally designed. In response, SSC San Diego quickly produced a prototype universal tool mount that could accept a variety of excavation and neutralization implements. The intent was to provide for simple field interchange of common EOD tools, as well as to facilitate future incorporation of emergent solutions.¹⁸ This design was eventually incorporated into the iRobot *PackBot* combination tool/lift kit that is now commercially available (see Figure 9).



Figure 9. The iRobot Tool/Lift Kit. The universal tool mount is on the left (front of the robot).

SSC San Diego is currently working on a number of functional improvements to the MTRS EOD robots at the request of NAVEODTECHDIV. Several designs for attachment of joint-service EOD tools are being developed and tested on MTRS *PackBot* and *Talon* robots.

Apart from these spiral-development efforts, RSP is also refurbishing a large number of Vanguard MK2 robots returned from Iraq as part of the MTRS down-select process. These robots will soon be available for loan to state and local law-enforcement and homeland security agencies, fire departments, and first responders.

RSP is also a source of contingency assets for operational needs. In FY-04, for example, nearly 30 small robots were supplied to EOD teams deployed to Iraq and Afghanistan for the inspection and subsequent removal of IEDs. Support continues for EOD technicians through loans, training, and technical assistance.¹⁹

9. CONCLUSIONS

JRP-supported efforts play a crucial part in SSC San Diego's role as a technology developer for joint-service robotics. In December 2005, in conjunction with the JRP-sponsored Unmanned Systems Capabilities Conference II, we performed a series of collaborative-behavior demonstrations involving multiple unmanned autonomous systems in a force-protection scenario.²⁰ These demonstrations included simultaneous control of an unmanned surface vehicle, three unmanned ground vehicles, and an unmanned aerial vehicle using the Multi-robot Operator Control Unit with the JAUS protocol.

In the simulated threat scenario, an unknown group of amphibious commandos landed on the beach and infiltrated inland. Pre-positioned radar and vibration sensors from the FIRRE project detected the incursion, and the Man-portable Perimeter Protection system (funded by the Defense Threat Reduction Agency) automatically provided confirming video of two armed intruders heading east. The MDARS-E robot, equipped with an automatic weapon and a UGV marsupial carrier, was dispatched to intercept the threat. A second MDARS-E vehicle with an intrusion-detection payload was also dispatched to provide backup. The USV, already patrolling off the coast, was redirected south by the MOCU operator to assess from the sea. MOCU also launched an autonomous helicopter (from the AUMS project) to obtain low-altitude mission-planning imagery and real-time reconnaissance of the incursion area. Executing GPS waypoint navigation, the helicopter entered a low-level (100-foot) hover to provide video surveillance. Based on the helicopter imagery, MOCU next commanded the MPRS URBOT to approach the north entrance of an abandoned underground bunker, a possible refuge for the intruders. Meanwhile, MDARS-E successfully engaged and neutralized one intruder with the Networked Remotely Operated Weapon System (NROWS). The second intruder took refuge in the underground bunker.

Serving as a temporary surrogate for the URBOT, an All Terrain Robotic Vehicle (ATRV) was sent via MOCU to the bunker entrance using GPS waypoint navigation. (The miniaturization of sensors that will allow the MPRS URBOT to perform the functions of the ATRV is currently happening under the MPRS project.) The ATRV seamlessly transitioned to SLAM navigation (developed under the TechTXFR project) and autonomously mapped and searched the interior of the bunker, finding a .50-calibre machine gun and the second intruder. The ATRV uploaded an augmented virtual world model of the bunker to the MOCU operator, fused with icons and real-time visual snapshots marking the locations of both the weapon and intruder.

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